Small Scale Liquefier Development

GTI RD&D Organization

Research & Deployment

Robert Stokes
Vice-President

Distribution & Pipeline Technology

Steve Gauthier
Executive Director

- **Pipeline Design & Construction**
- **Pipeline Operation & Integrity**
- **Pipeline Inspect & Corrosion**
- **Metering & Automation**
- **Materials/Plastics**

Hydrogen Energy Systems

Gerry Runte
Executive Director

- **Hydrogen**
- **Fuel Processing**
- **Low-Temperature Fuel Cells**
- **High-Temperature Fuel Cells**
- **Vehicle Fuel Infrastructure**

Energy Utilization

Hamid Abbasi
Executive Director

- **Residential Appliances**
- **Commercial Appliances & Use**
- **Industrial Processes & Use**
- **Central Power Generation**
- **Air Quality**

Gasification & Gas Processing

Francis Lau
Executive Director

- **Gasification & Hot Gas Cleanup**
- **Process Engineering**
- **Thermal Waste Stabilization**
- **Gas Processing & Conditioning**
- **Catalytic Synthesis**

Exploration & Production Technology

Kent Perry
Executive Director

- **Earth Science**
- **Resource Assessment**
- **Gas Storage**
- **Liquefied Natural Gas**
- **Gas Hydrates**

Distributed Energy Applications

John Kelly
Executive Director

- **Distributed Generation Products, Services, and Technologies**
- **Space Conditioning**
- **Combined Heat and Power**

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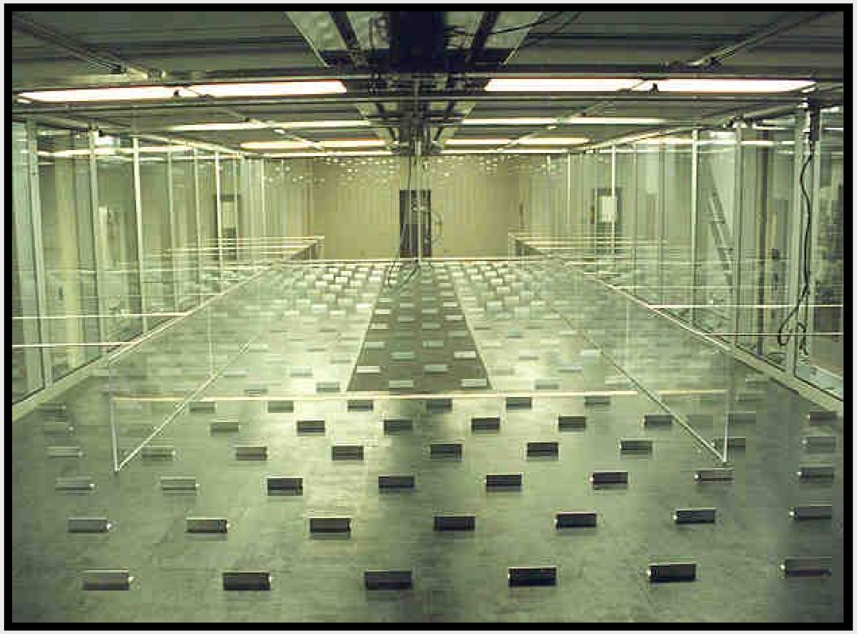
GTI LNG Capabilities

> Education
> Information
> Interchangeability and Gas Quality
> Small Scale Liquefaction
> LNG Storage
> Siting and Safety Modeling

LNG Safety



Model Development & Verification

- Late 1970's Through 1998
- Approximately $12 Million Investment

LNG Safety Staff

Dr. Mike Du, GTI,
Modeling & Software

Dr. Liese Dallbauman, GTI,
Gas Dispersion Modeling

Dr. Colleen Sen, GTI,
Industry Liaison &
Technology Dissemination

Dr. Jerry Havens, U. of Arkansas
Model Development &
Applications

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LNG Safety Models

- DEGADIS
  - Describes Atmospheric Dispersion of Denser Than Air Gases – Flat Surface, Obstruction Free Terrain
- LNGFire3
  - Calculates Thermal Exclusion Zone For LNG Fire Scenarios
- FEM3A
  - Dispersion Model Accounting For Terrain Features and Obstacles
  - Applicable To A Wide Range of Gases/Materials

Small Liquefaction and LNG Markets

Sources

- Pipeline Natural Gas
- Gas Resource Deployment
  - Stranded natural gas resources
  - Opportunity Fuels
    - Landfill gas, wastewater gas, digester gas

Uses

- LNG for Utilities and Industrials
  - Peakshaving/standby for gas utilities & industrials
  - Remote community natural gas service
- LNG for Vehicles
  - Medium and heavy-duty trucks and buses

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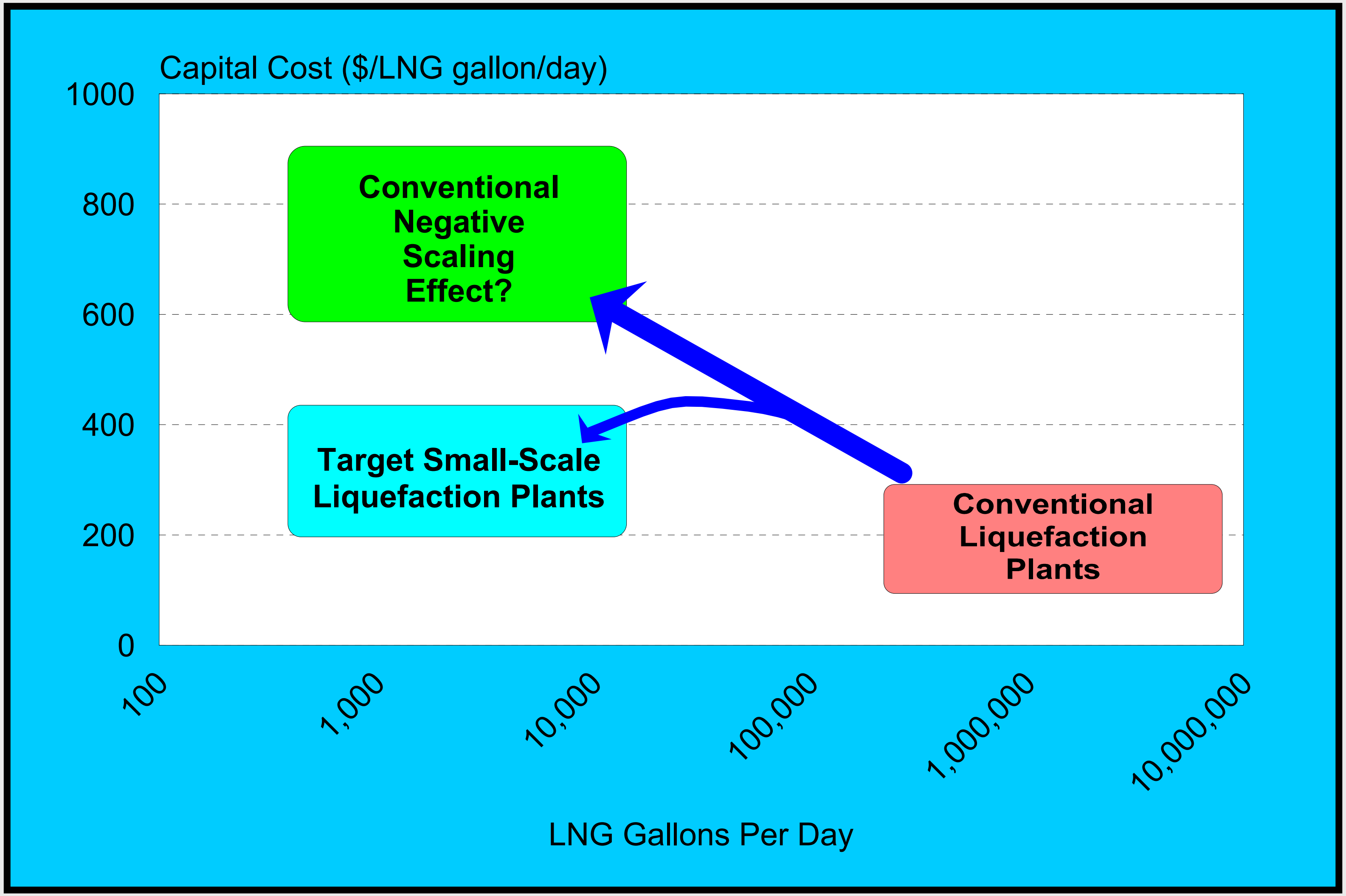
Small-Scale Liquefaction



Natural Gas Liquefaction Options

LIQUEFIER TYPE	OPERATING PRINCIPLE	REMARKS AND TRADEOFFS
Precooled Joule-Thomson (JT) Cycle	A closed-cycle refrigerator (e.g. using Freon or propane) pre-cools compressed natural gas, which is then partially liquefied during expansion through a JT valve	Relatively simple and robust cycle, but efficiency is not high. Used in Anker Gram onsite liquefier for LNG truck fueling (which is no longer operating).
Nitrogen Refrigeration Cycle (also called closed Brayton/Claude cycle)	Nitrogen is the working fluid in a closed-cycle refrigerator with a compressor, turboexpander, and heat exchanger. Natural gas is cooled and liquefied in the heat exchanger.	Simple and robust cycle with relatively low efficiency. Using multiple refrigeration stages can increase efficiency. Used in CryoFuel Systems Hartland LFG liquefier demonstration.
Cascade Cycle	A number of closed-cycle refrigerators (e.g. using propane, ethylene, methane) operating in series sequentially cool and liquefy natural gas. More complex cascades use more stages to minimize heat transfer irreversibility.	High-efficiency cycle, especially with many cascade steps. Relatively expensive liquefier due to need for multiple compressors and heat exchangers. Cascade cycles of various designs are used in many large-capacity peakshaving and LNG export plants.
Mixed-Refrigerant Cycle (MRC)	Closed cycle refrigerator with multiple stages of expansion valves, phase separators, and heat exchanger. One working fluid, which is a mixture of refrigerants, provides a variable boiling temperature. Cools and liquefies natural gas with minimum heat transfer irreversibilities, similar to cascade cycle.	High-efficiency cycle that can provide lower cost than conventional cascade because only one compressor is needed. Many variations on MRC are used for medium and large liquefaction plants. ALT-El Paso Topock LNG plant uses MRC. GTI is developing simplified MRC for small plants (under 10,000 gpd).
Open Cycles with Turboexpander, Claude Cycle	Classic open Claude cycle employs near-isentropic turboexpander to cool compressed natural gas stream, followed by near-isenthalpic expansion through JT valve to partially liquefy gas stream.	Open cycle uses no refrigerants other than natural gas. Many variations, including Haylandt cycle used for air liquefaction. Efficiency increases for more complex cycle variations.
Turboexpander at Gas Pressure Drop	Special application of turboexpander at locations (e.g. pipeline city gate), where high-pressure natural gas is received and low-pressure gas is sent out (e.g., to distribution lines). By expanding the gas through a turboexpander, a fraction can be liquefied with little or no compression power investment.	This design has been applied for peakshaving liquefiers, and it is currently being developed by INEEL in cooperation with PG&E and SoCalGas to produce LNG transportation fuel. Very high or "infinite" efficiency, but special circumstances must exist to employ this design.
Stirling Cycle (Phillips Refrigerator)	Cold gas (usually helium closed cycle using regenerative heat exchangers and gas displacer to provide refrigeration to cryogenic temperatures. Can be used in conjunction with heat exchanger to liquefy methane.	Very small-capacity Stirling refrigerators are catalog items manufactured by Phillips. These units have been considered for small-scale LNG transportation fuel production.
TADOPTR	TADOPTR = thermoacoustic driver orifice pulse tube refrigerator. Device applies heat to maintain standing wave, which drives working fluid through Stirling-like cycle. No moving parts.	Currently being developed by Praxair and LANL for liquefaction applications including LNG transportation fuel production. Progressing from small-scale to field-scale demonstration stage.
Liquid Nitrogen Open-Cycle Evaporation	Liquid nitrogen stored in dewar is boiled and superheated in heat exchanger, and warmed nitrogen is discharged to atmosphere. Counterflowing natural gas is cooled and liquefied in heat exchanger.	Extremely simple device has been used to liquefy small quantities of natural gas. More than one pound of liquid nitrogen is required to liquefy one pound of natural gas. Nitrogen is harmless to atmosphere. Economics depends on price paid for liquid nitrogen.

Adapted from USA Pro/California Energy Commission with modifications

GTI Mixed Refrigerant System

- Mixed Refrigerant Liquefier
  - Uses specially designed, patented multi-component refrigerant
  - Standard HVAC screw compressor technology for reliability and low cost
  - Electric motor or gas engine drive
  - Initial 250 gal/day lab prototype built and tested
  - Pre-Commercial 1000 gal/day unit built and tested
    - Current system uses natural gas engine drive
  - Design scale-up to 5000 to 10,000 gallons/day
  - Sponsored by U.S. Department of Energy, Brookhaven National Lab, and GRI/GTI

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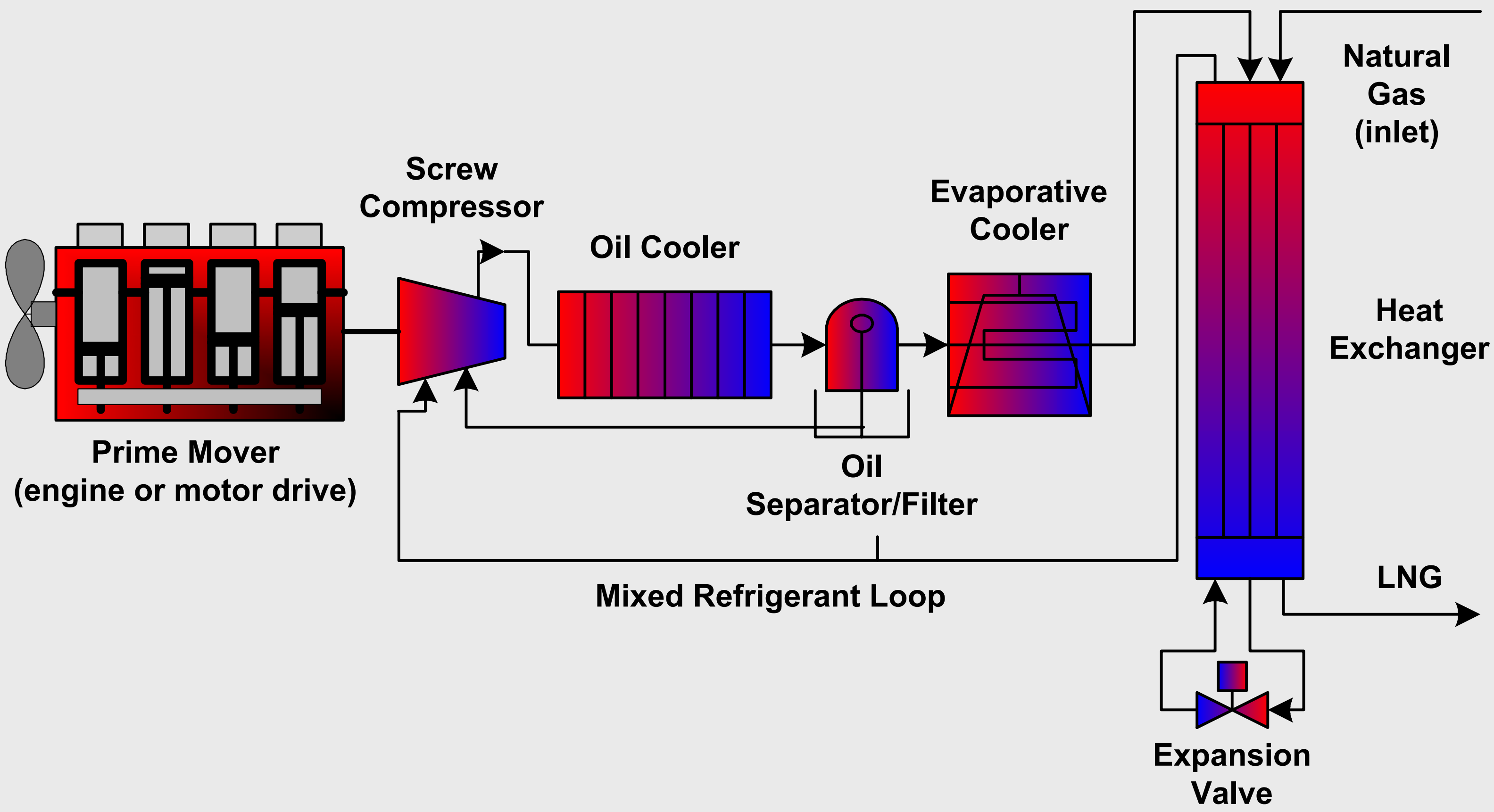
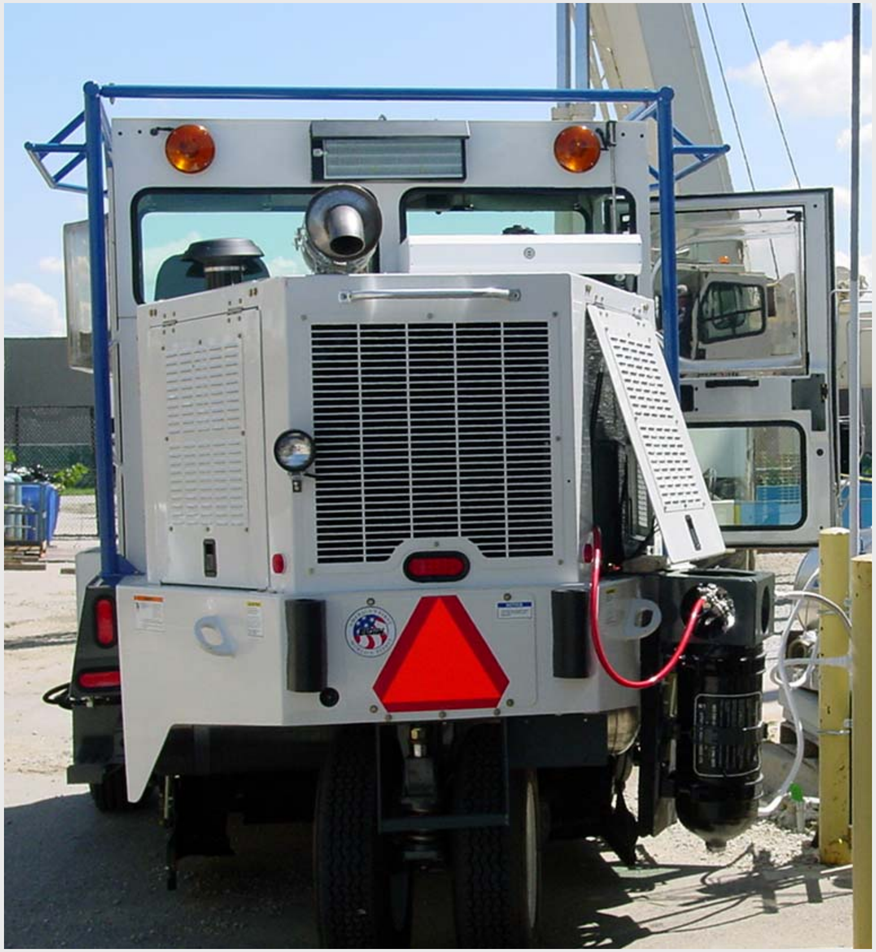
DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA

GTI Mixed Refrigerant System Simplified Process Schematic



Mixed Refrigerant Liquefier 1000 gpd Prototype System

Fueling LNG Vehicle



Elgin Sweeper

LNG Vehicle

J.C. Carter
LNG Nozzle

System Testing Results

> With natural gas engine drive
  – About 25% of natural gas used in liquefaction
  – Variable fuel operating cost: 9.4¢/LNG gallon (natural gas at $4/MMBtu)

> With electric drive system
  – Use 29.3 kWh/MMBtu of natural gas liquefied
  – Variable fuel operating cost: 14.5 ¢/LNG gallon (electricity at $0.07/kWh)

> System efficiency improvements likely at 5000 to 10,000 gpd
  – Lower variable fuel operating costs

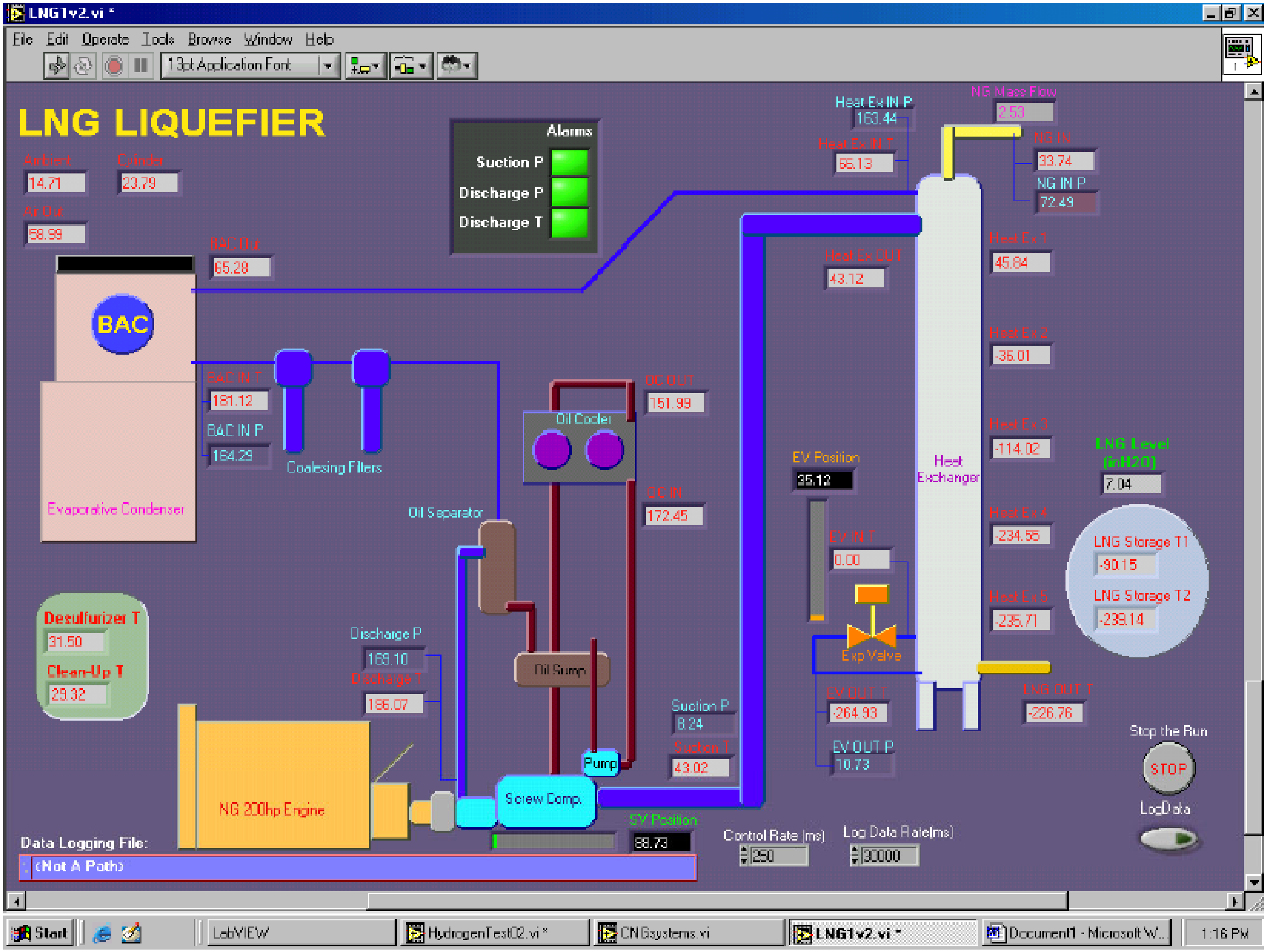
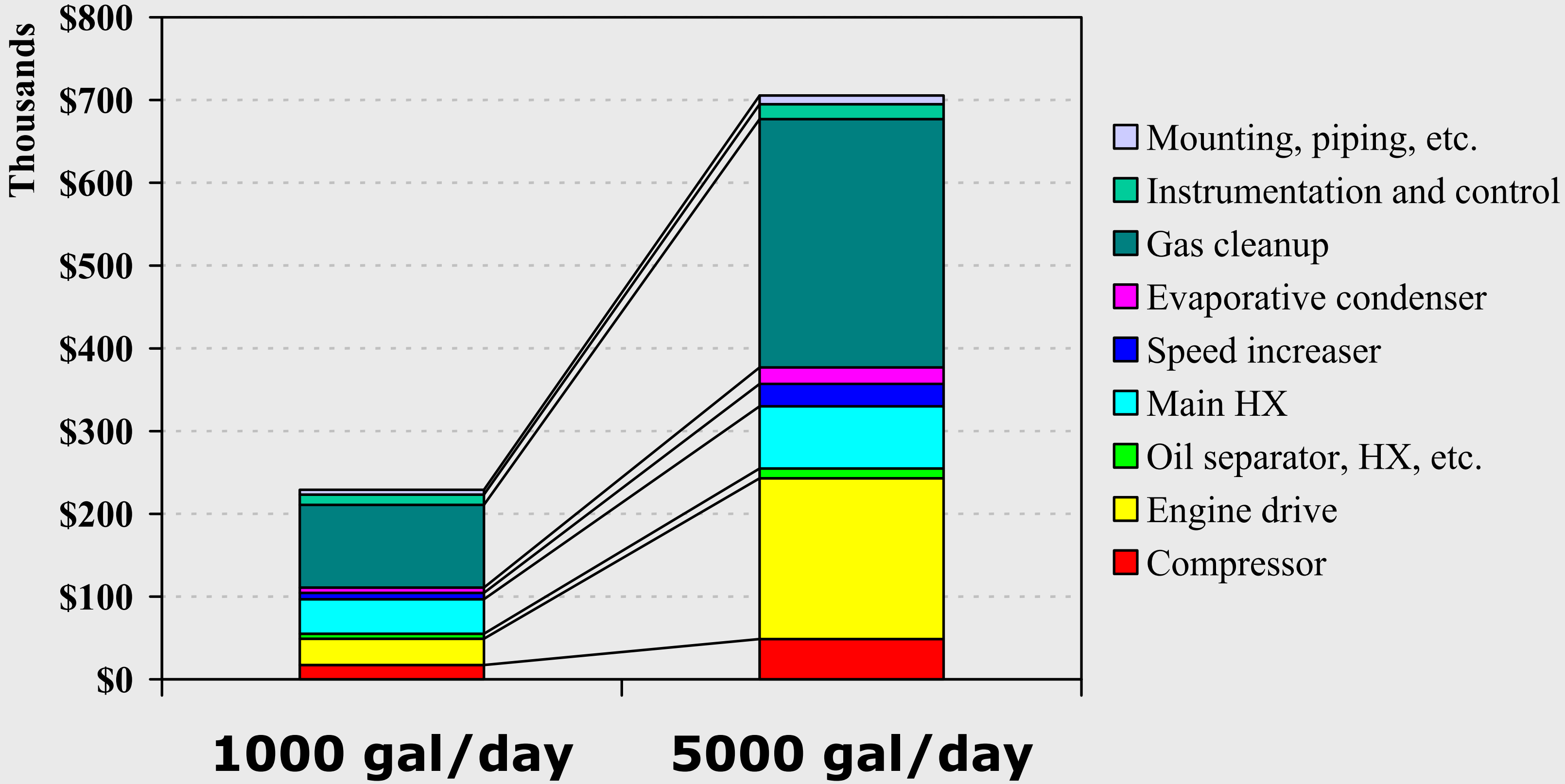


Figure 14: Data Acquisition Display on Laboratory Computer For Run 3/10/03-1

Capital Cost Comparison

Including Estimated Costs for Gas Cleanup*

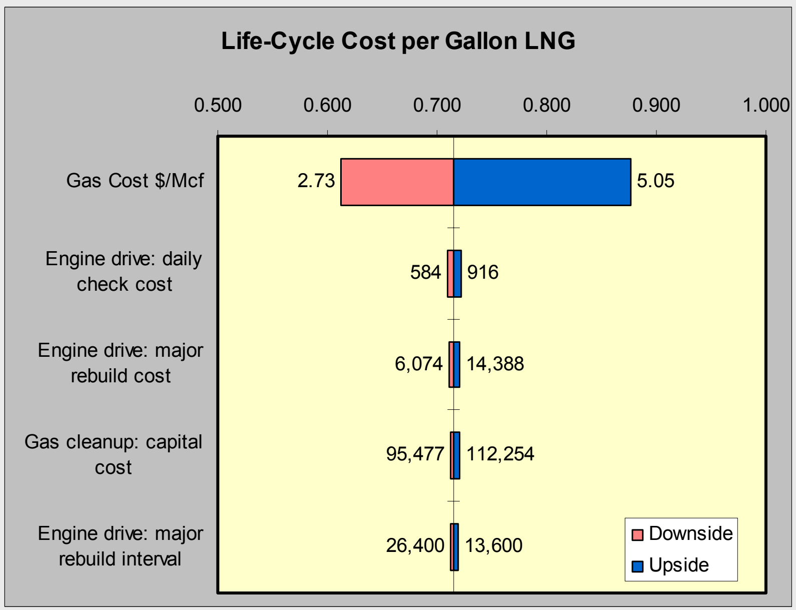


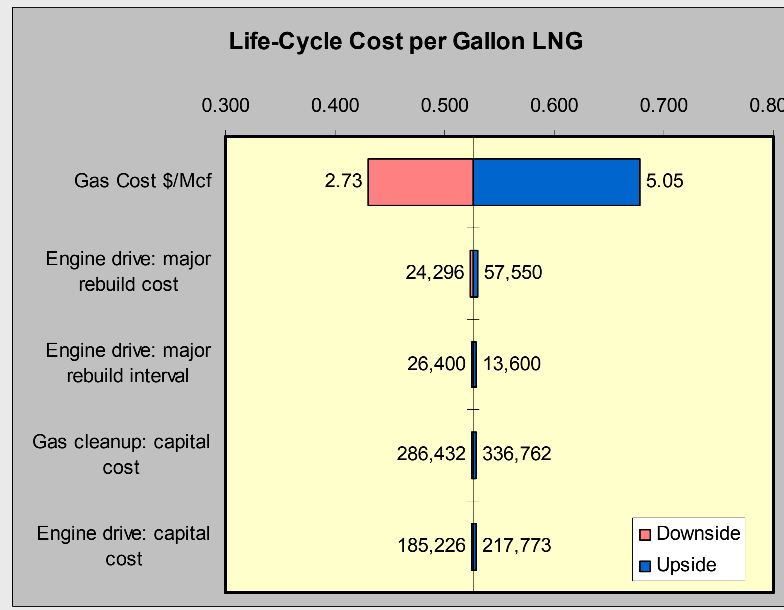
* Cost estimates do not reflect market selling price

Sensitivity

Scenario 1: Retail Gas w/ Clean Up

- **1,000 gal/day**
  - $0.72/gal life-cycle cost
- **5,000 gal/day**
  - $0.53/gal life-cycle cost





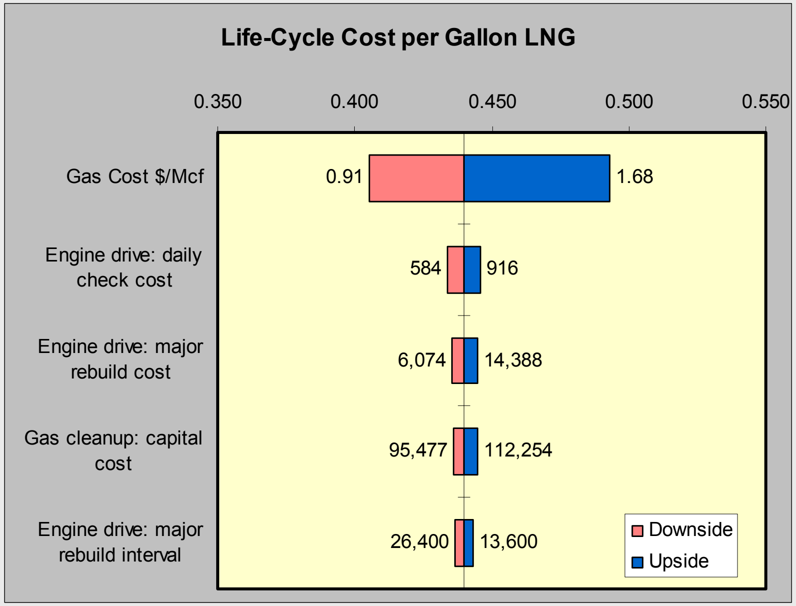
System economics sensitive to size and natural gas cost

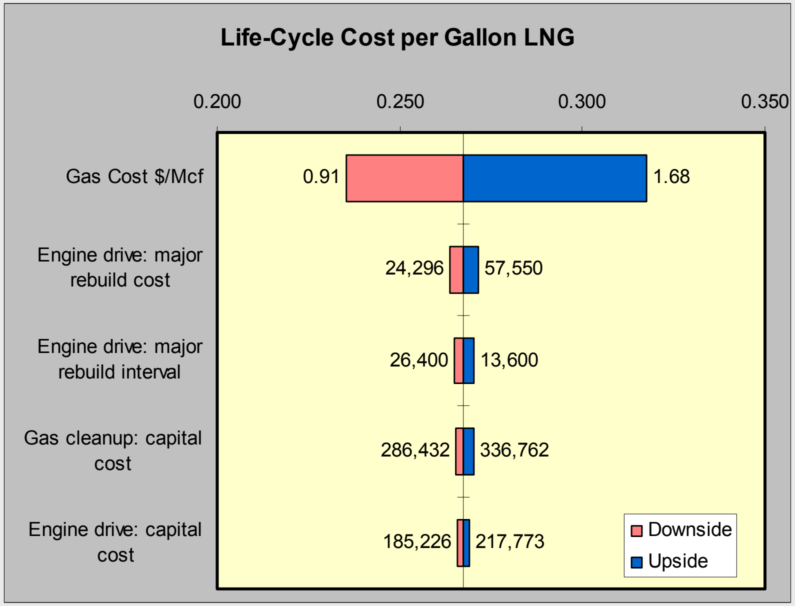
* Cost estimates do not reflect market selling price

Sensitivity

Scenario 2: Byproduct Gas (Landfill Gas)

- 1,000 gal/day
  - $0.44/gal life-cycle cost
- 5,000 gal/day
  - $0.27/gal life-cycle cost





* Cost estimates do not reflect market selling price

Conclusions

- Small Scale Liquefaction Technically Viable
- System Economics Sensitive to Size & Fuel Cost
- Fuel Clean-up Systems Key Area
  - Low-cost approaches for removing water and CO_2 levels (and trace compounds) – especially for opportunity fuels

	1,000 gal/day	5,000 gal/day
Retail Natural Gas	\$0.72	\$0.53
Byproduct Gas	\$0.44	\$0.27

Next Steps

> Ongoing discussions with potential partners, project developers, and licensees
> Diverse set of potential market applications and drivers
> Design and engineering work focusing on 5000 to 10,000 gallon per day systems

Contacts

> Please contact the following person for more information and to explore licensing opportunities

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GTI Commercial and Investments Group

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